


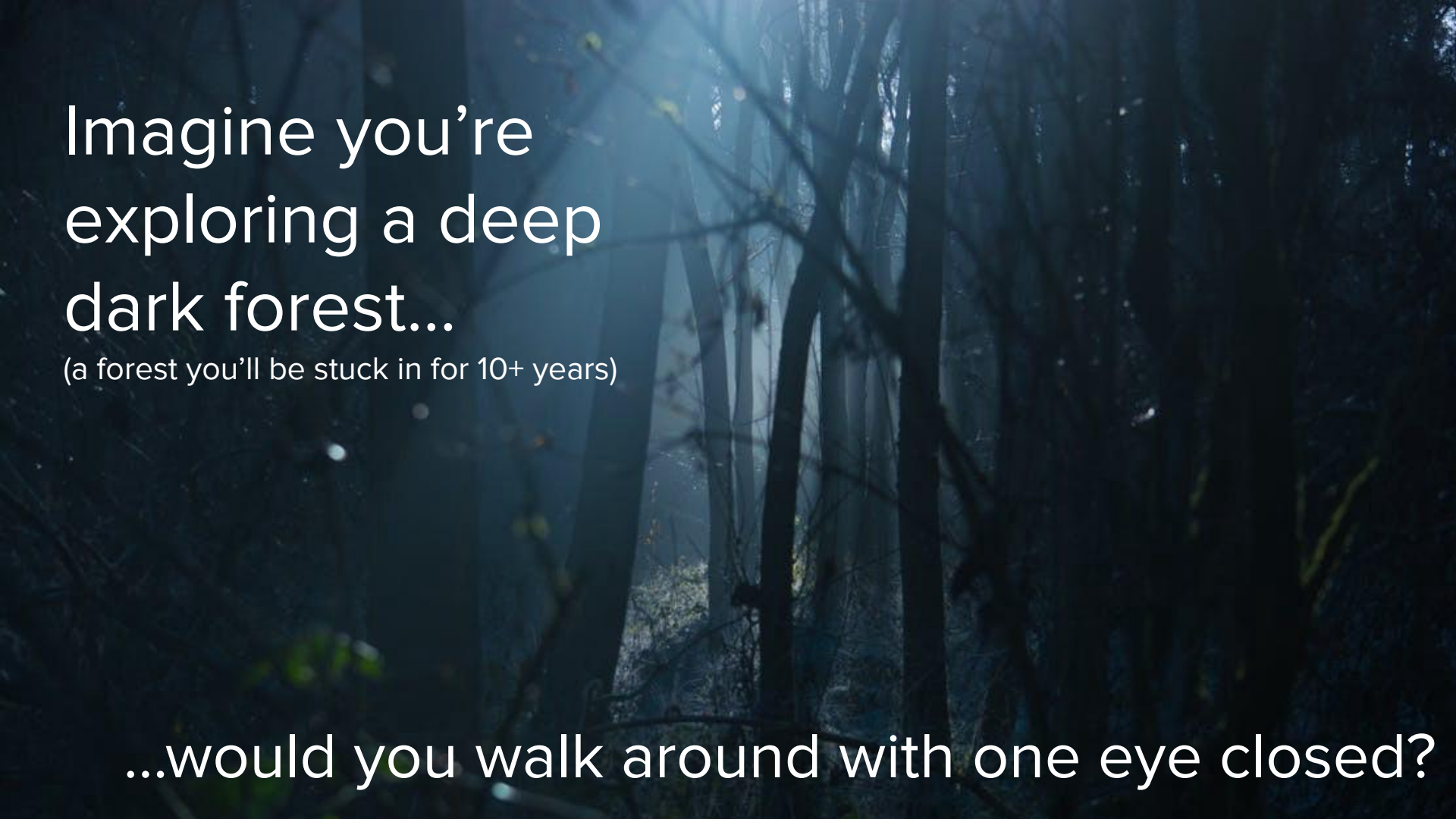
# Qpix light readout

A Blue Sky MOOD talk by Elena Gramellini  
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Imagine you're  
exploring a deep  
dark forest...

(a forest you'll be stuck in for 10+ years)

A dark, misty forest with tall, thin trees and a blueish tint. The scene is dimly lit, with light filtering through the trees, creating a sense of depth and mystery. The text is overlaid on the left side of the image.

Imagine you're  
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dark forest...

(a forest you'll be stuck in for 10+ years)

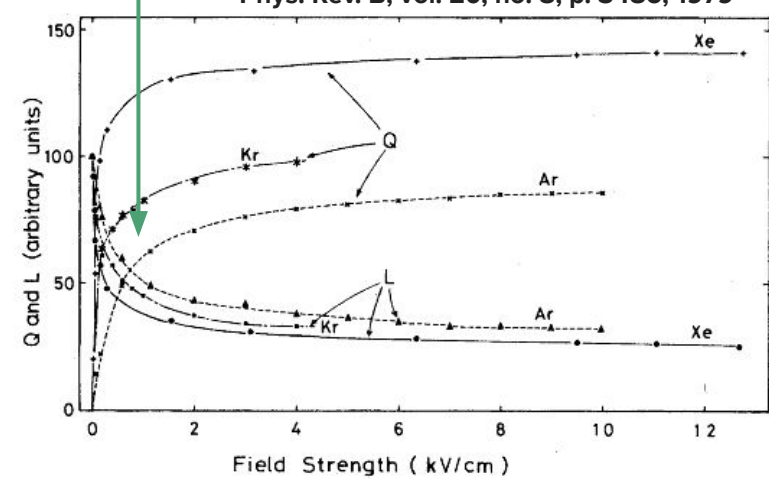
...would you walk around with one eye closed?

# Why light and charge?

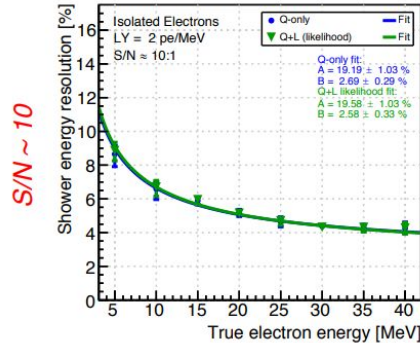
At  $E = 500$  V/cm (typical LArTPC field),  $\frac{1}{2}$  of half of energy released by charged particle in LAr goes in scintillation light  $\rightarrow$  Light holds  $\frac{1}{2}$  of the information quantity.

**DUNE LIVES HERE!**

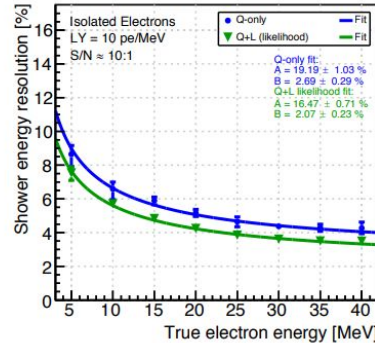
Phys. Rev. B, vol. 20, no. 8, p. 3486, 1979



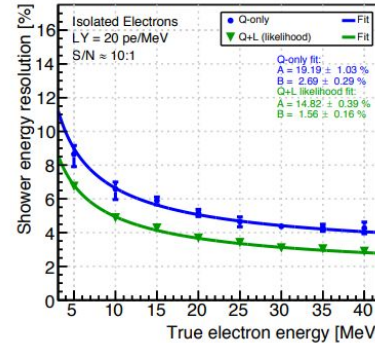
LArIAT arXiv:1909.07920



LY = 2 pe/MeV

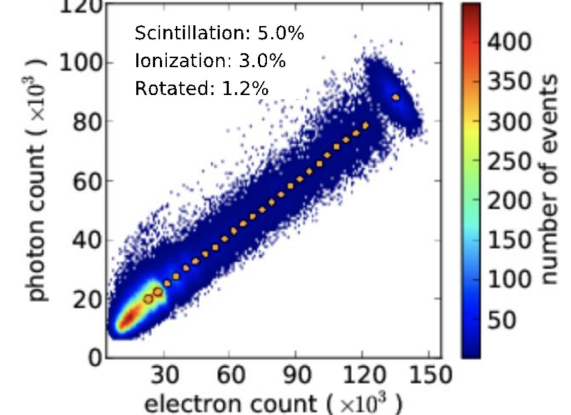


LY = 10 pe/MeV



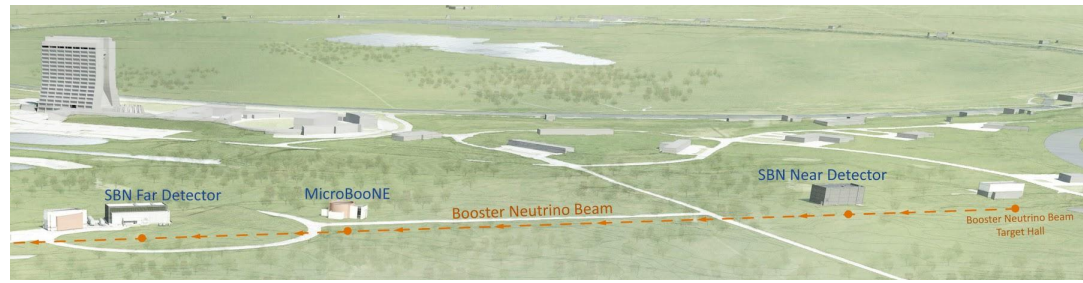
LY = 20 pe/MeV

EXO-200 arXiv:1908.04128





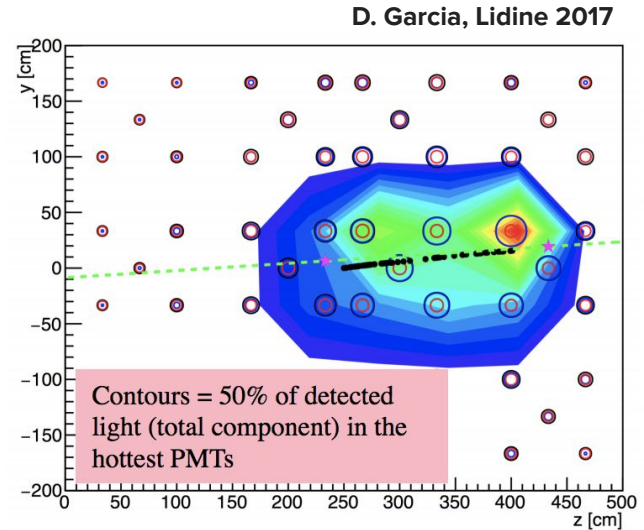
# SBN(D) as light testbench



The revamping of **ICARUS** included potentiate the light collection system (more PMTs). **MicroBooNE's** PDS original design was focused on triggering on the light... now timing and positional information from the PDS is also used for cosmic discrimination at analysis level.

**SBND** is going to be the cadillac of PDSs in current large LArTPC generation:  
high granularity:  $\sim 100$  ARAPUCAs + 120 8" PMTs  
high coverage (sensitive elements cover  $\sim 50\%$ )  
foils for reflected light (position resolution from timing).  
Simulation results: 40 cm position res w/ PMTs alone

Is this the way to light semantic segmentation?



# Light Requirements for DUNE

Description	Specification (Goal)	Rationale
Light Yield	$> 0.5 \text{ PE / MeV (min)}$	$>99\%$ of nucleon decays can be tagged
Time Resolution	$< 1\mu\text{s}$	1mm position resolution for 10 MeV supernova $\nu$
Spatial localization in y-z plane	$< 2.5 \text{ meters}$	Enables “accurate” TPC to PDS match

## From the DUNE TDR Appendix:

*Physics deliverable: the PD system should be able to provide a calorimetric energy measurement for high-energy events complementary to the TPC energy measurement. Neutrino energy is an observable critical to the success of the oscillation physics program, and a second independent measurement can provide a cross-check that reduces systematic uncertainties or directly improves resolution for some types of events.*

# Thoughts on current design

## Limited real estate for Light Collection System.

How much of the available APA has photon detection capability?

**X-Arapuca Design:**  $130 \text{ m}^2/10\text{kT}$

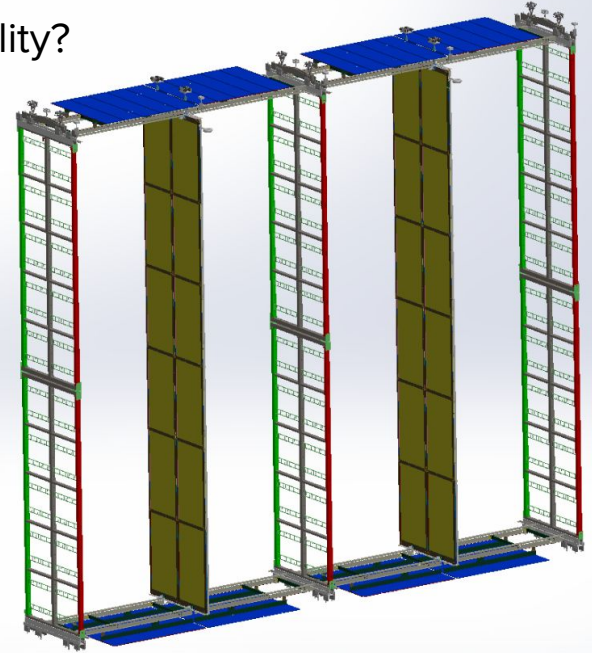
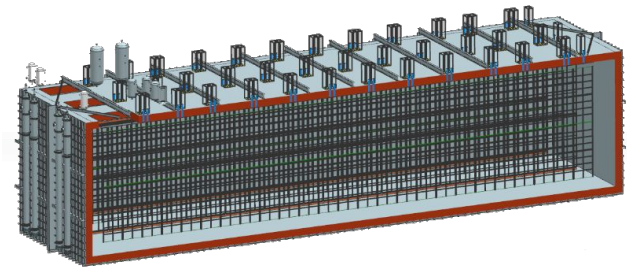
Window area for each supercell  $(435.24 \text{ cm}^2) \times 10$   
supercells/APA  $\times 152$  APA's per 10kT  $\times 2$  (Double sided)

**APA Active Area:**  $\sim 200000 \text{ m}^2/10\text{kT}$

$(135,700 \text{ cm}^2) \times 152$  APAs/10kT

**Surface area instrumented is  $\sim 0.06\%$**

- It is actually effectively less when you take efficiency of the device into account



*\*\*\* Not meant to disparage the current technology in any way...instead meant to give context to the problem*

# What if the whole APA could collect light?

**A pixel based readout would seem to only complicate the problem!**

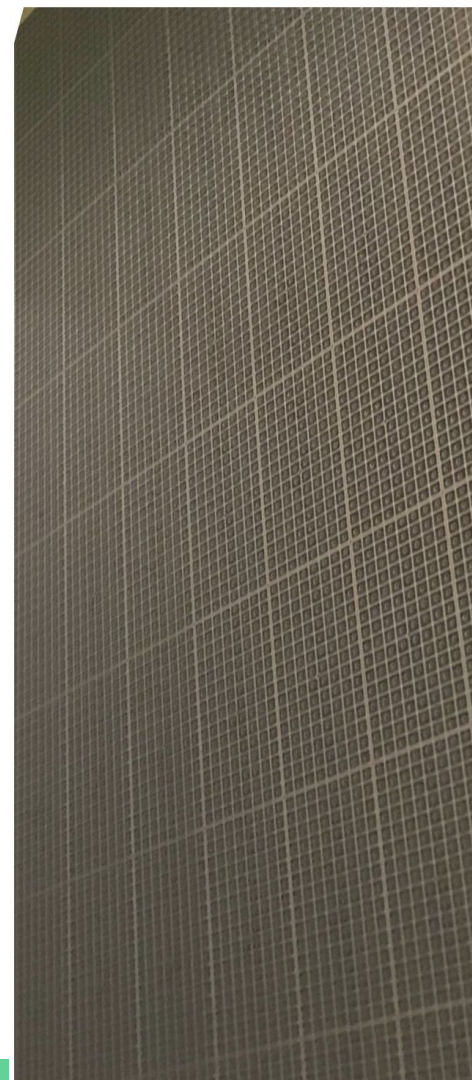
Now your entire anode is opaque to light!

**Yet, a pixel plane sensitive to UV photons and ionization charge SIMULTANEOUSLY would be a major breakthrough**

Your effective instrumented area becomes enormous

Even if the device has low efficiency you have a huge gain

***Note: The ideas proposed here have the potential for quite good UV photon efficiency***





Unorthodox charge  
readouts need unorthodox  
light solutions.

Nanoplatelets & Perovskite.

Dual purpose pixel (A-Se).

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readouts need unorthodox  
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Nanoplatelets & Perovskite.

Dual purpose pixel (A-Se).

Both solutions require research in  
material science... within the Q-Pix  
consortium, Argonne National Lab offers  
the partnership needed.

# ANL UV conversion material research

Ongoing program to develop nanoparticle wavelength shifters tuned to specific absorption wavelength and emission wavelength.

**Goal:** identify nanoparticle for detection of light at 128 nm and 175 nm (Argon & Xenon) and study applicability to both neutrino and DM experiments.

ANL role: test candidates and characterize in terms of absorption, wavelength-shift size, emission.

Research on materials for direct conversion of UV to electron/(holes) draws on expertise of Argonne Materials Science Division (MSD). Specifically, Alex Martinson (MSD) has experience from solar conversion materials and optoelectronic processes. He is providing 20% of his time researching materials and processes specific for liquid argon UV detection.

Stolen from Bob Wagner, ANL.

# Nanoplatelets

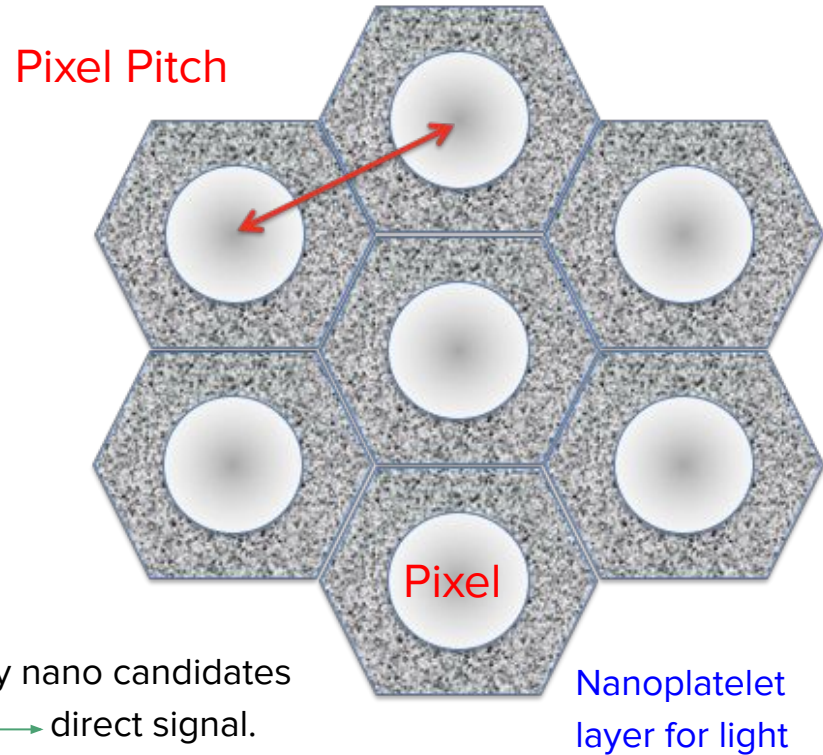
The charge collection pixels are isolated using the photon sensors.

The pixel plane is made of a substrate material with nanoplatelets deposited on the substrate, readout on the back side (outside of TPC)

Nanoplatelets absorb VUV photons, generate electrons: direct conversion of photons to current.

Current SBIR grant with CapeSym, Inc.(8/19–4-20) to identify nano candidates sensitive to 128 nm and 175 nm → form into nanoplatelets → direct signal.

*Doping Argon with hundreds of ppm Xenon converts all 128 nm light to 175 nm – may already have suitable candidates to start incorporating into nanoplatelets*



Stolen from Steve Magill, ANL.



# Perovskites

In addition to amorphous selenium, perovskites are a potentially very interesting candidate for UV photodetection.

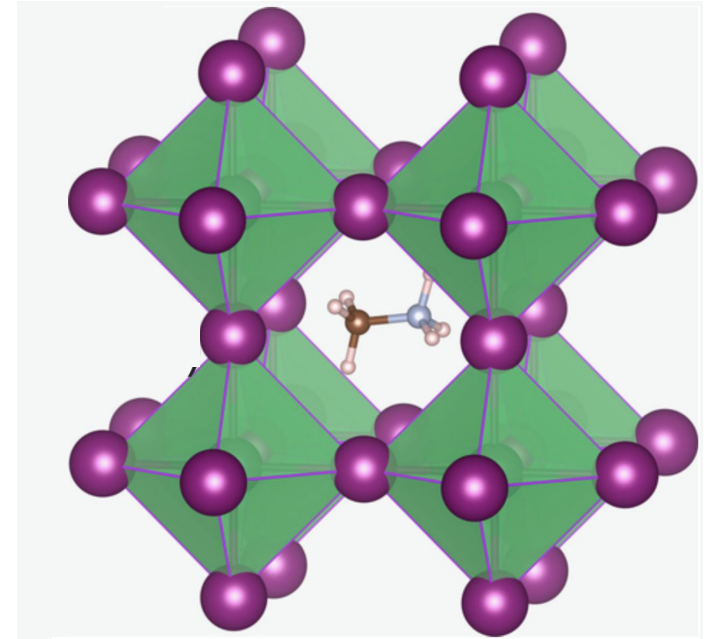
**Perovskite:** specifically  $\text{CaTiO}_3$  but used as a generic term for any material with the same crystal structure.

Possible base material for high-efficiency photovoltaics:

Methylammonium halides are being studied for their high charge carrier mobility (example at right)



Most perovskites have poor UV performance but studies have extended useful range into DUV (200-350nm).



Methylammonium lead triiodide

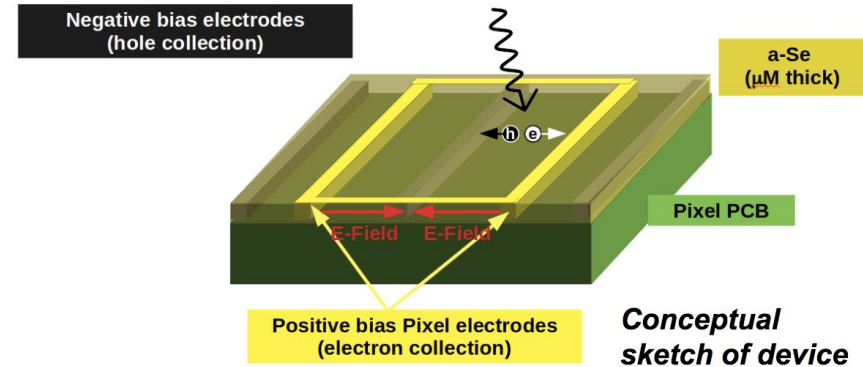
Stolen from Bob Wagner, ANL.

# Dual Purpose A-Se Pixels

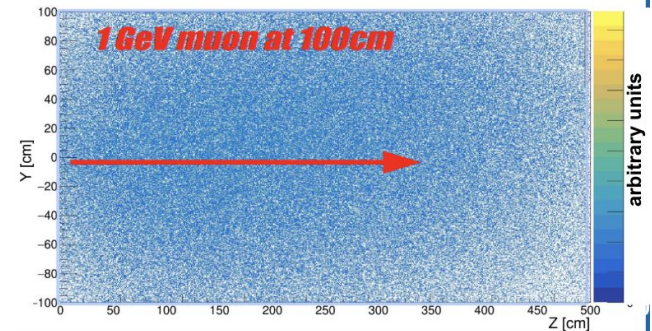
Pixel coating with photo-conducting material: can the pixels collecting ionization charge be used to detect UV photons?

Currently exploring different thin-film photo-conductors which may offer an opportunity

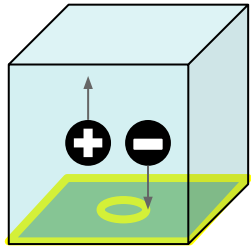
Exploring amorphous Selenium's properties  
Commonly used in X-Ray digital radiography devices



Incident photons from a 1 GeV muon at 100 cm



# Why is A-Se interesting?



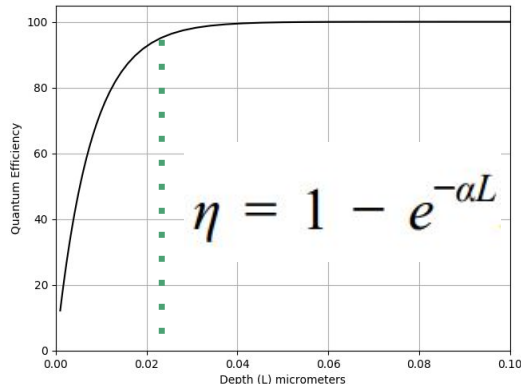
A-Se

Pixel  
electrode

Assume you can apply a uniform electric field on a block of a-Se some micrometers thick where the electron-hole pair is being created.

To figure out the charge produced, you need to know how thick a layer of

amorphous selenium will give you a high QE for the single photon of the right energy → Absorption coefficient!



The literature on amorphous selenium reports an attenuation coefficient  $\alpha \sim 130 \mu\text{m}^{-1}$  for photons at 128 nm, resulting in a **QE than 99% for thin coatings ( $> 1 \mu\text{m}$ )**.

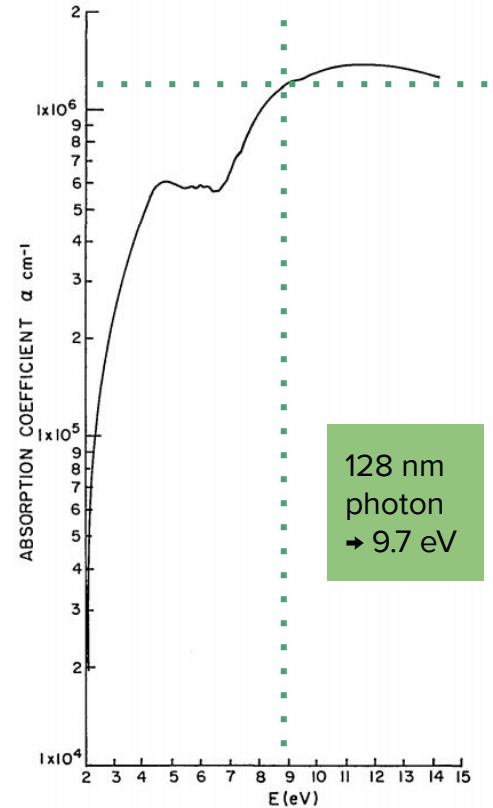


FIG. 6. The spectral dependence of the absorption coefficient,  $\alpha$ , of amorphous selenium.

# What about the transport?

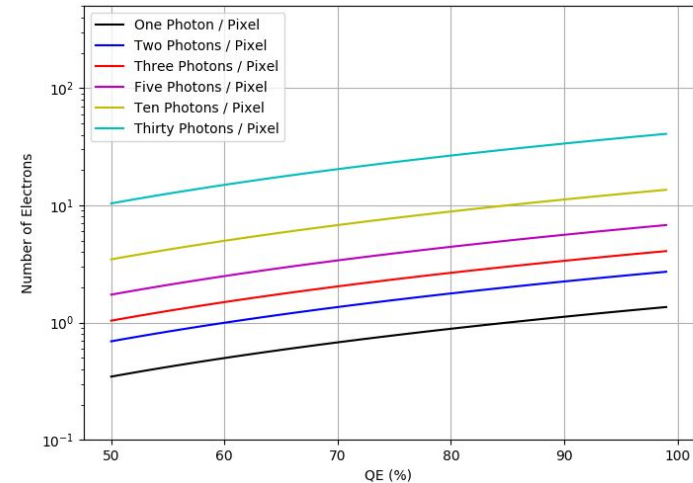
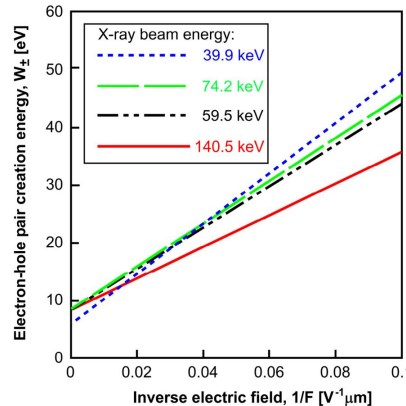
The amount of charge deposited into the a-Se is given by  
 Where  $q$  is the fundamental charge of the electron, and  $W_{\pm}$  is a property of the mobility of a-Se which depends on the electric field and temperature.  $\Delta E$  is the amount of energy absorbed. In a single 4mm by 4 mm pixel, a reasonable assumption for  $\Delta E$  is 26.46 eV... You start with  
 ~ 3 photons per pixel at 9.7eV / photon and 0.9 QE.

$$\Delta Q = q \frac{\Delta E}{W_{\pm}},$$

Literature gives an approximated values of  $W_{\pm} = 7.07$  eV (and a favorable trend with temperature)...

So, transport in the A-Se  
 $\Delta Q \sim 26.36/7.07$  e

3 photons coming in...  
 3.7 electrons going out





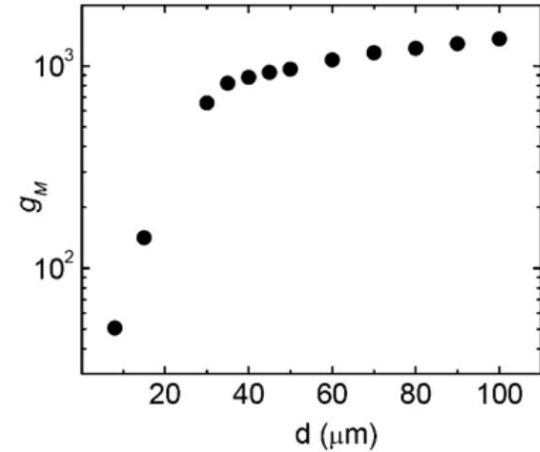
# What about the signal? Estimate summary

You started with 99% Quantum Efficiency for 128 nm photons with a a-Se layer that is >1 micrometers thick

If 3 photons fall on the 4 mm pad, such high QE gives you ~ 3+ electron-hole pairs (where you're being conservative for transport → only 1 electron per photon).

At the theoretical breakdown voltage of a-Se (~ 90 Volts/ $\mu\text{m}$ ) for 100 micrometers thick deposition, you can a gain factor up to  $\sim 1.5 \cdot 10^3$ : ~ 4000 electrons for three 128nm photons on a 4mm pixel pad.

**These numbers would be very consistent with the current Q-Pix design choice of being between 0.3 and 1 fC (1800 and 6000 electrons) for a RTD (Reset Time Difference).**



**Figure 10** Maximal achievable multiplication gain for different a-Se layer thicknesses.

# Modeling of a-Se to understand optical properties w/ VUV light

Professor Muhammad Huda at UTA (condensed matter theorist) and his student (Sajib Barman) have started an A-Se model to better understand and predict the optical-electronic properties we could expect when exposed to 128 nm photons.

They start w/ Generalized Gradient Approximations in Density Functional Theory and will add further approximations to capture experimentally measured properties. From there, can they use phenomenological models to predict the optical-electronic properties.

A promising way to reduce the breakdown voltage is the use of dopands, whose effects can be studied within the constructed model.

A qualitative agreement for the VUV energy region between old data and a first, crude version of the simulation has been shown... off to a good start, but... we need more experimental data!

A proposal to build first prototypes that can feedback into this studies has been submitted to FNAL.

# Potential of Dual Purpose Pixel Solution

The photocathode coverage is close to 100% by construction: by coating or engineering all the anode pixels, the photocathode coverage coincides with the anodic plane coverage.

Absorption of direct VUV light removes any hit in conversion efficiency taken in technology based on wavelength shifting.

If we can achieve gain multiplication in the A-Se, a very high QE is expected (>90%).

Extremely high granularity built in by construction: basic light detection unit 4 by 4 mm.

A study of A-Se absorption in the visible would also be interesting to improve homogeneity in the detection along the drift direction. A solution including reflective foils at the cathode could be explored.

# Conclusions



Kiloton scale pixel based

LArTPC's require “unorthodox” solutions.

Q-Pix is a consortium is exploring these solutions for both charge and light detection.

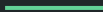
Exploring “blue sky” ideas to design a discovery machine.



*Q-Pix consortium would like to thank  
the DOE for its support via  
DE-SC0020065 award*



Let's build the  
best possible  
machine for  
discovery...



Let's build the  
best possible  
machine for  
discovery...

..and let  
Nature,  
(and our youngest  
grad student)  
surprize us!

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Thank you